Primordial Black Hole Hotspots and Nucleosynthesis

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based on arXiv:2501.05531, with M. Fairbairn and L. Heurtier

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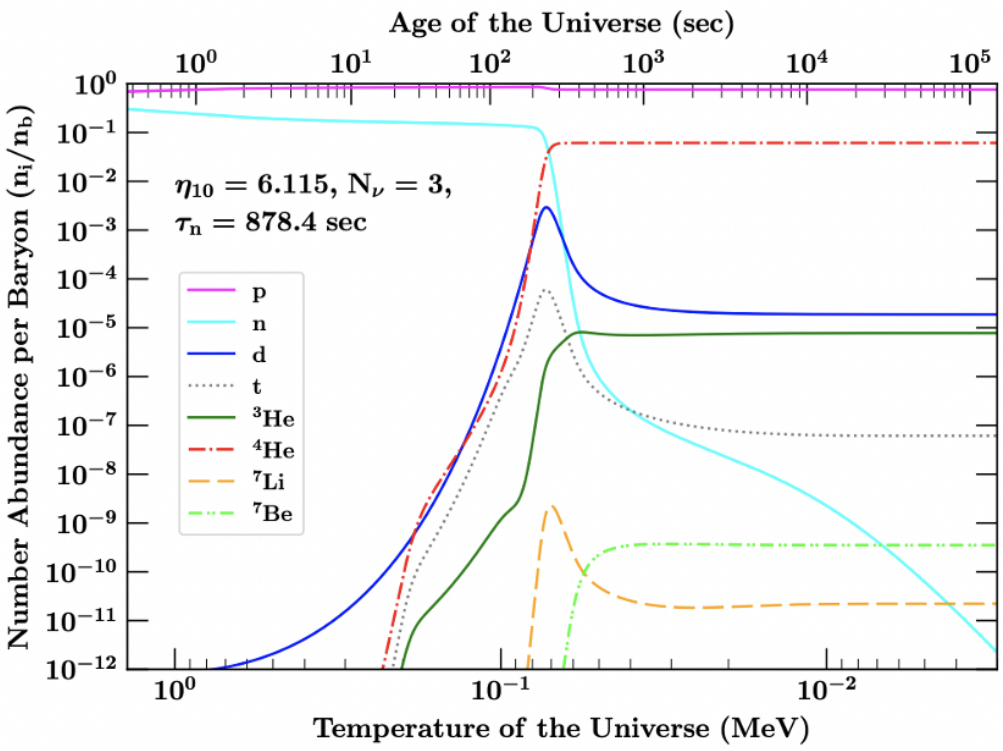
Outline

1. Motivation: PBH and BBN
2. Photodissociation
3. PBH hotspots
4. Hotspots effects on photon flux
5. Universal spectrum and BBN limits
6. Results
7. backup slides

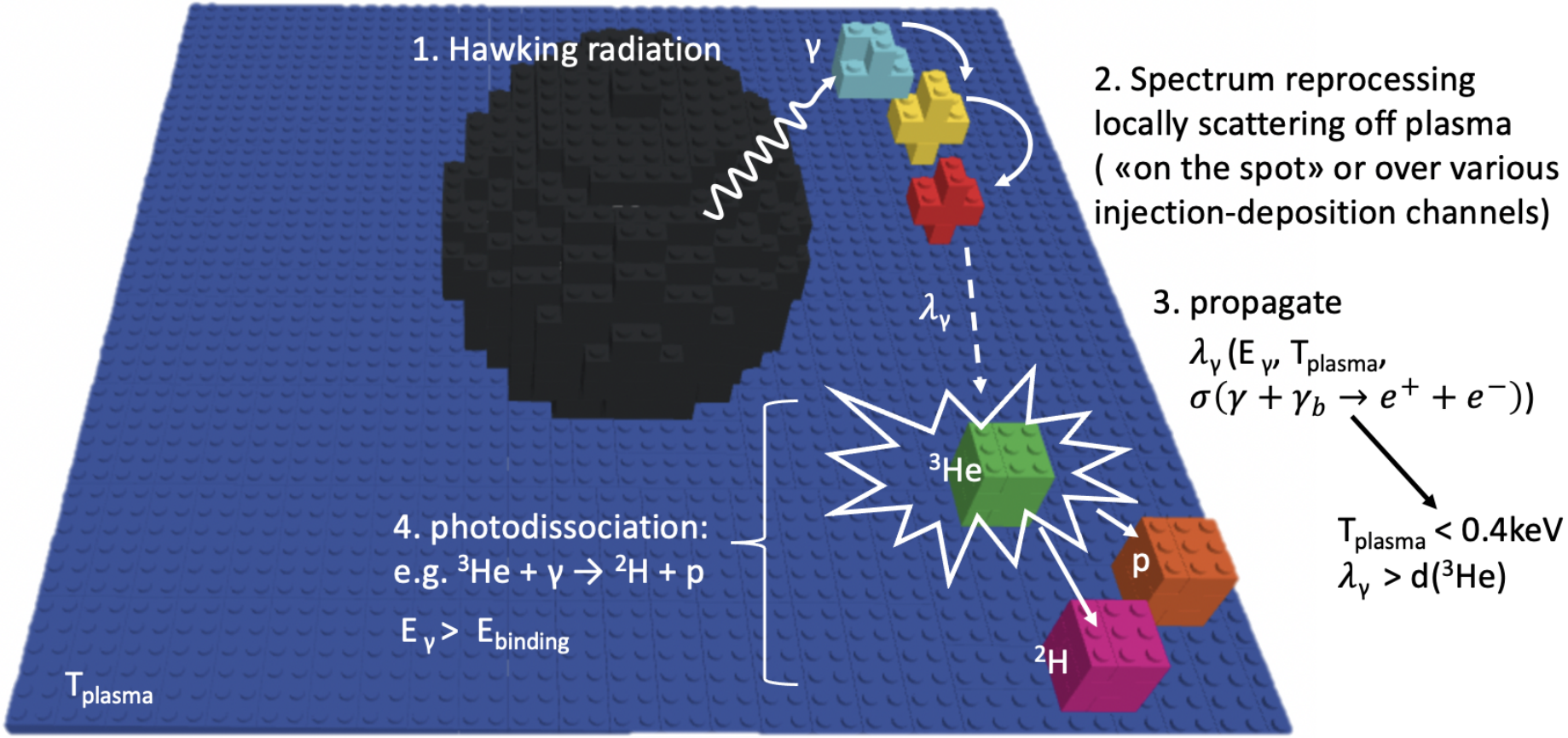
PBH and BBN



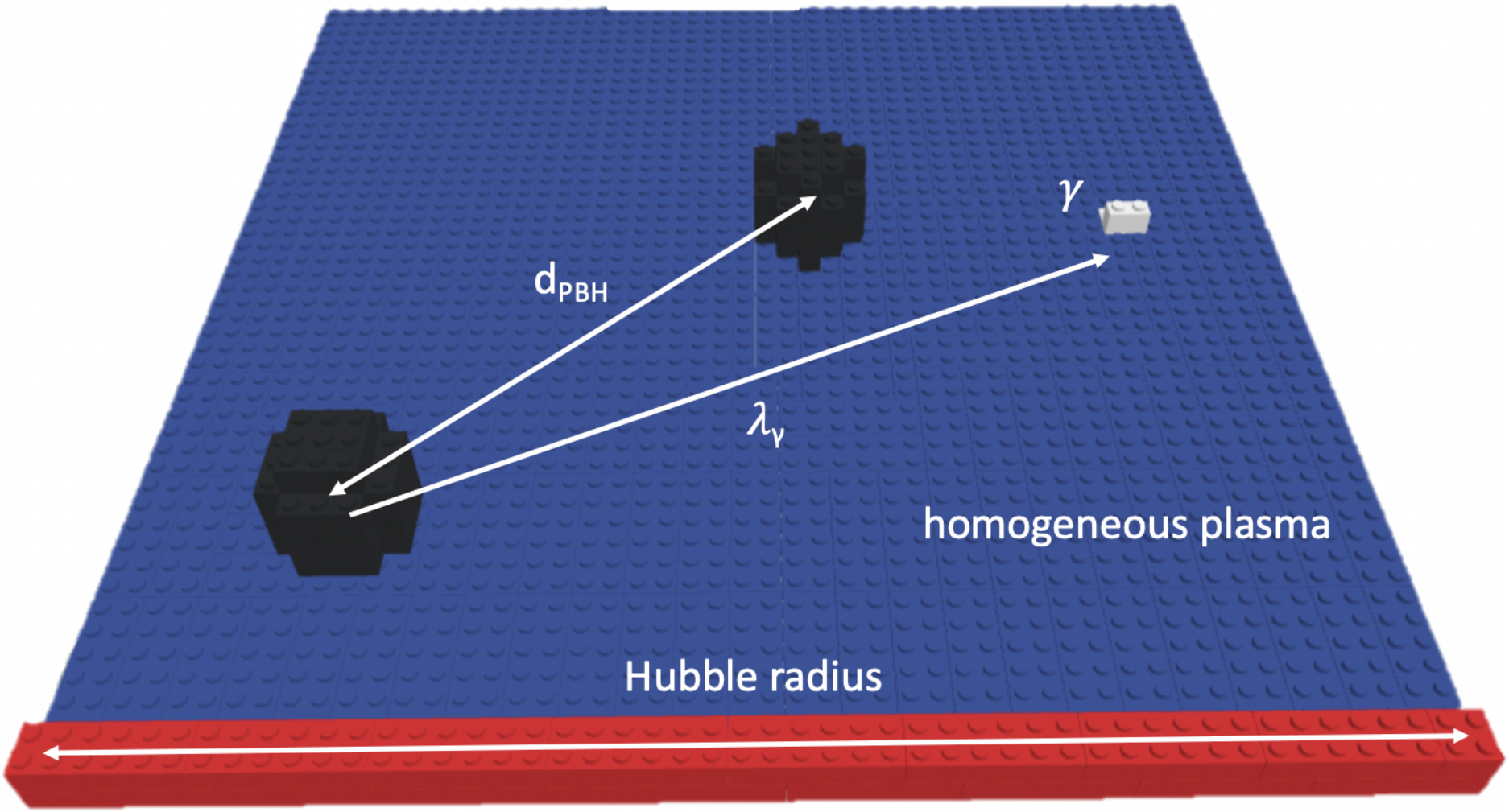
(Yeh, Olive, Fields 2023)

- energy and particle injection
- photodissociation
- hadrodissociation

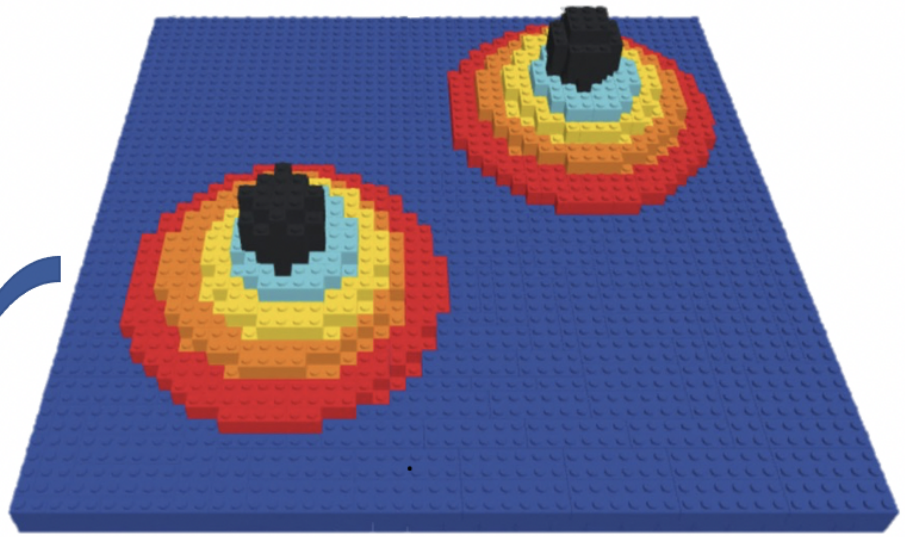
Basics of photodissociation

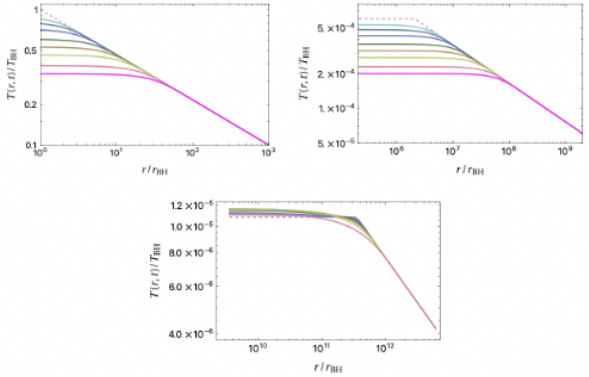


Assumption of homogeneity and isotropy

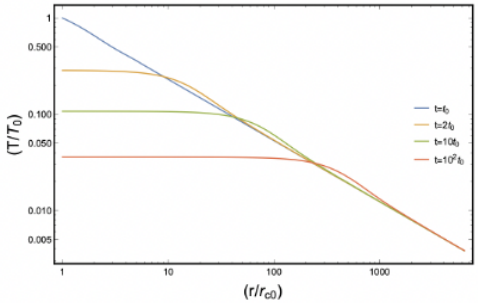


localisation effects: PBH hotspots

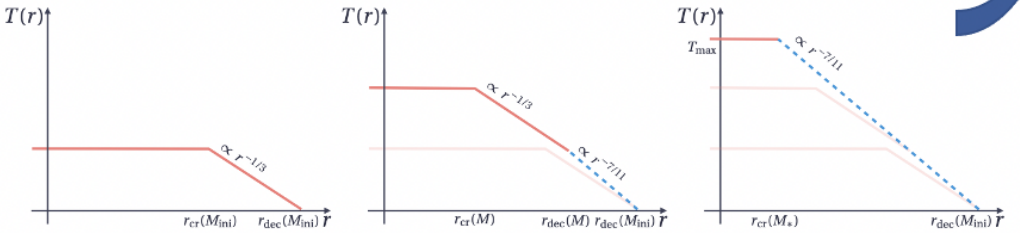




3. Boltzmann- improved numerical treatment confirms 1. where local thermal eq. assumption holds (He, Kohri, Mukaida, Yamada 2022)

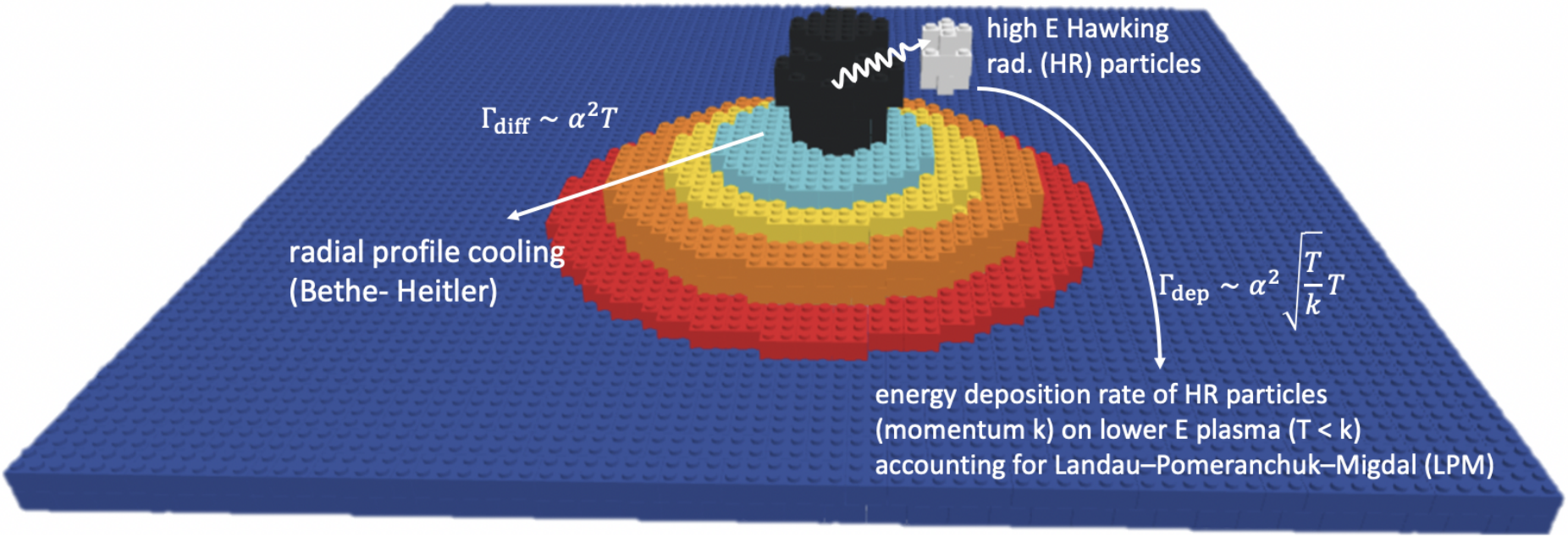


1. qualitative (Das, Hook 2021)

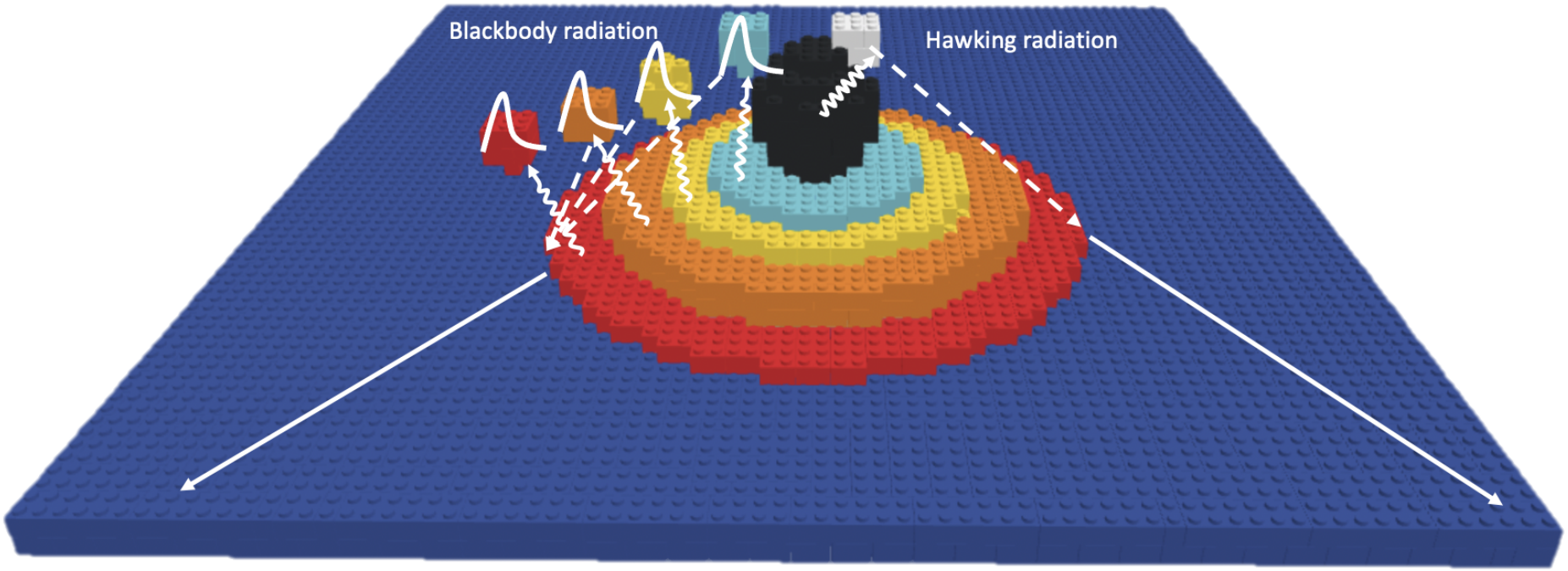


2. Landau- Pomeranchuk-Migdal (LPM) effect in Hawking radiation energy deposition (He, Kohri, Mukaida, Yamada 2022)

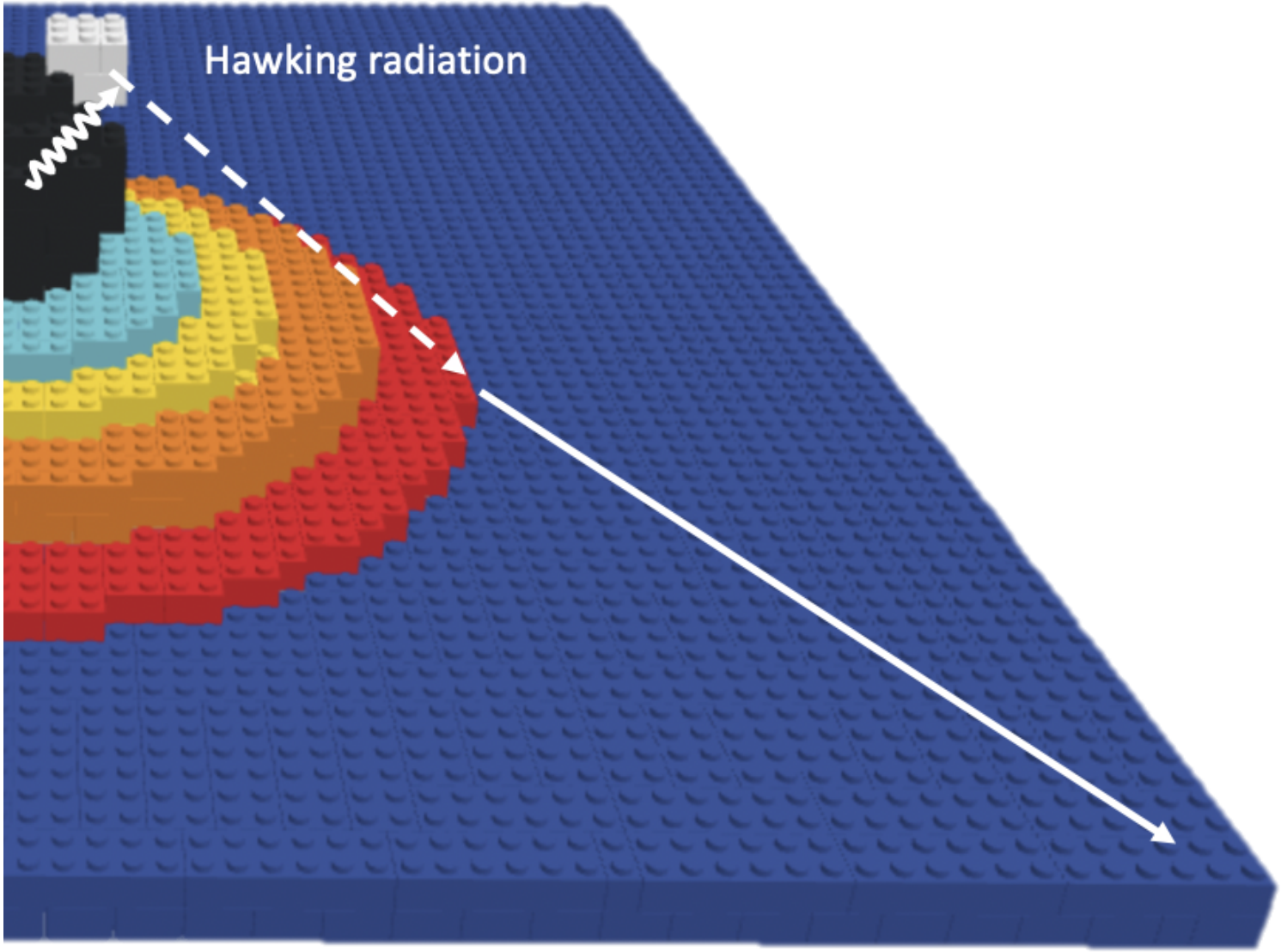
Hotspot dynamics



Hotspot effects on photon flux



Shielding



Shielding

- **optical depth** of a HS of radius $r_{\rm HS}$ for photons of energy E:

$$\mathrm{OD}^{\gamma}(E) \equiv \int_0^{r_{\rm HS}} \frac{dr}{\lambda(E, T(r))} \tag{1}$$

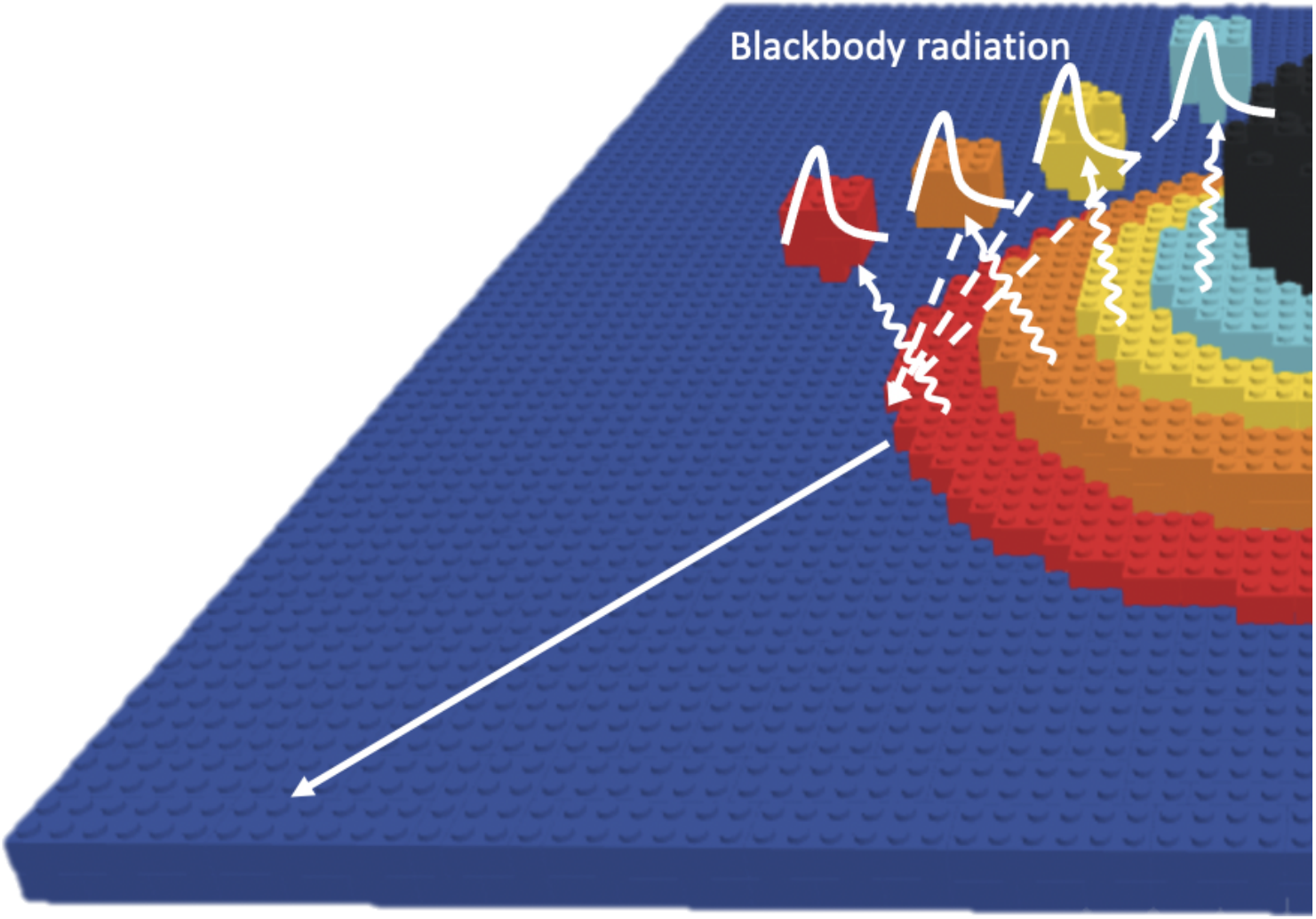
- **escape probability**:

$$P^{\gamma}_{\rm esc}(E) \equiv e^{-\mathrm{OD}^{\gamma}(E)} \tag{2}$$

- modified photon **emission rate**:

$$\left.\frac{dN}{dEdt}\right|_{\rm secondary} \longrightarrow \left.\frac{dN}{dEdt}\right|_{\rm secondary} \times P^{\gamma}_{\rm esc}(E). \tag{3}$$

Black body radiation



Black body radiation

- **local** optical depth of the HS for photons emitted at the same location:

$$\mathrm{OD}^{\gamma}(E) \equiv \int_0^{r_{\mathrm{HS}}} \frac{dr}{\lambda(E, T(r))} \rightarrow \mathrm{OD}^{\gamma}(E, r) \equiv \int_r^{r_{\mathrm{HS}}} \frac{dr'}{\lambda\left(r', E_{\gamma}\right)} \tag{4}$$

- **escape probability** as a function of **radius**:

$$P_{\mathrm{esc}}^{\gamma}(E) \equiv e^{-\mathrm{OD}^{\gamma}(E)} \rightarrow P_{\mathrm{esc}}^{\gamma}(E, r) = e^{-\mathrm{OD}^{\gamma}(E, r)} \tag{5}$$

Blackbody radiation

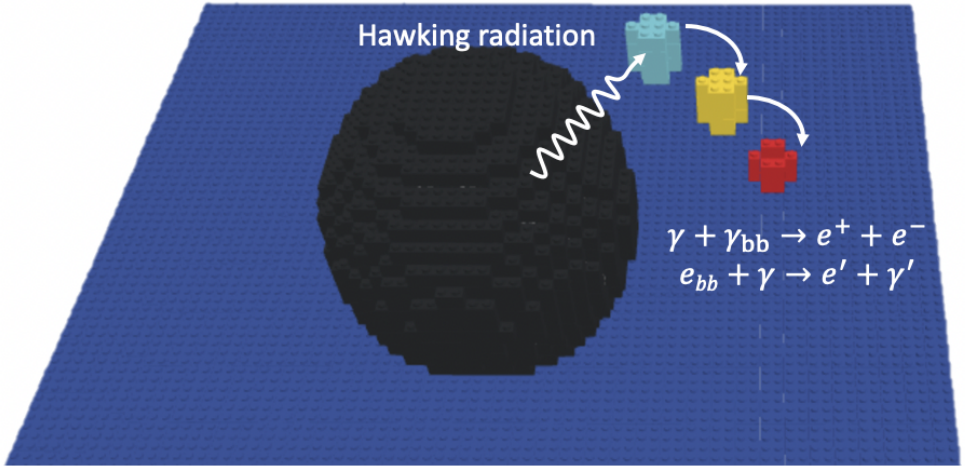
- **emission rate** of outgoing photons of energy E emitted by the plasma from a **thin shell** of radius r:

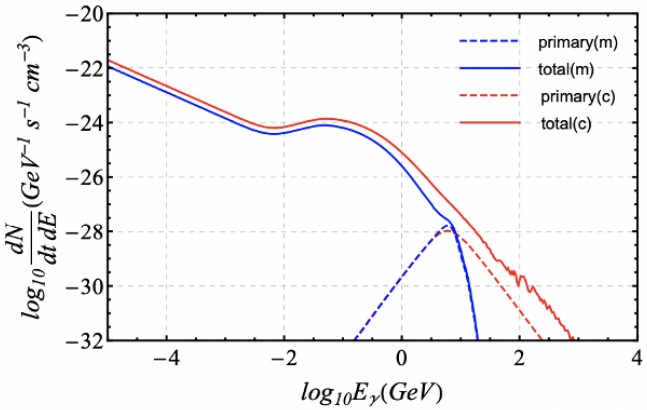
$$\Phi_{\rm HS}(E, T(r), r) \equiv \frac{1}{2}\frac{E^2}{\pi^2}\frac{1}{e^{E/T(r)}-1}4\pi r^2$$

- emission rate integrated over HS **volume**:

$$\left.\frac{dN}{dtdE}\right|_{\rm HS} = \int_0^{r_{\rm HS}} \left(\frac{d\Phi_{\rm HS}}{dr}\cdot P^{\gamma}_{\rm esc}(E,r)\right) dr. \tag{6}$$

Universal spectrum and BBN limits





(Luo, Chen, Kusaka, Kajino 2021)

- in homogeneous Universe → **induced low energy spectrum** only dependent on the initial energy E_0 of the high-energy parent particle

Universal spectrum and BBN limits

- **induced universal spectrum** at low energy:

$$\left.\frac{dN}{dE}(E,E_0)\right|_{\text{universal}} = K_0 \begin{cases} (E/E_X)^{-3/2} & \text{for } E < E_X \\ (E/E_X)^{-2} & \text{for } E_X \leqslant E \leqslant E_C \\ 0 & \text{for } E_C < E \end{cases} \tag{7}$$

where

$$K_0 \equiv \frac{E_0}{E_X^2\left[2+\ln\left(E_C/E_X\right)\right]} \tag{8}$$

$E_X = m_e^2/(80T)$, **inverse-Compton scattering** threshold energy
$E_C = m_e^2/(22T)$, **electron-pair production** threshold energy.

Universal spectrum and BBN limits

- **universal spectrum** expected from PBH evaporation:

$$\left.\frac{dN}{dEdt}\right|_{\text{final}} = \int \left.\frac{dN}{dE_0dt}\right|_{\text{secondary}} \times \left.\frac{dN}{dE}(E,E_0)\right|_{\text{universal}} dE_0 \propto \int \left.\frac{dN}{dE_0dt}\right|_{\text{secondary}} \times E_0dE_0 \tag{9}$$

- assume $T_{Universe}$ outside HS does not evolve significantly over evaporation

$$\left.\frac{dN}{dE}\right|_{\text{final}} \propto \int dt \int \left.\frac{dN}{dE_0dt}\right|_{\text{secondary}} \times E_0dE_0 \tag{10}$$

Universal spectrum and BBN limits

- **rescaling** of uniform universe solution up to **transfer function**

$$\mathcal{T}(M) \equiv \frac{\int \frac{dN}{dEdt}\left(E_0\right)\Big|_{\text{secondary}} \times E_0 P^{\gamma}_{\text{esc}}\left(E_0\right) dE_0}{\int \frac{dN}{dEdt}\left(E_0\right)\Big|_{\text{secondary}} \times E_0 dE_0} \tag{11}$$

- use as proxy to estimate HS impact on **BBN photodissociation constraints**, by dividing the current limits on the PBH abundance by $\mathcal{T}(M)$.

Results

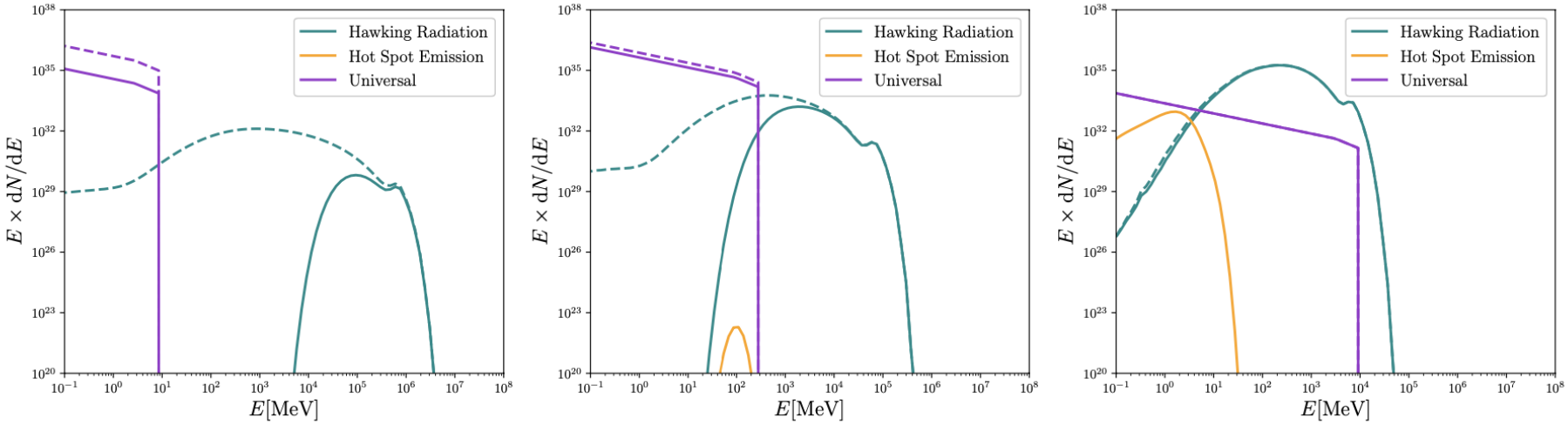


Fig. 1. Comparison of the emitted photon energy distributions for PBHs with initial masses equal to 10^{11}g (left panel), 10^{12}g (center panel), and 10^{13}g (right panel). Teal curves stand for the secondary photons emitted directly by Hawking radiation and photons emitted directly by the hot spot are depicted in orange. The corresponding universal spectrum induced by photon scattering off the plasma outside the hot spot is plotted in purple. Results considering (or ignoring) the presence of a hot spot are depicted using plain (dashed) lines.

Results

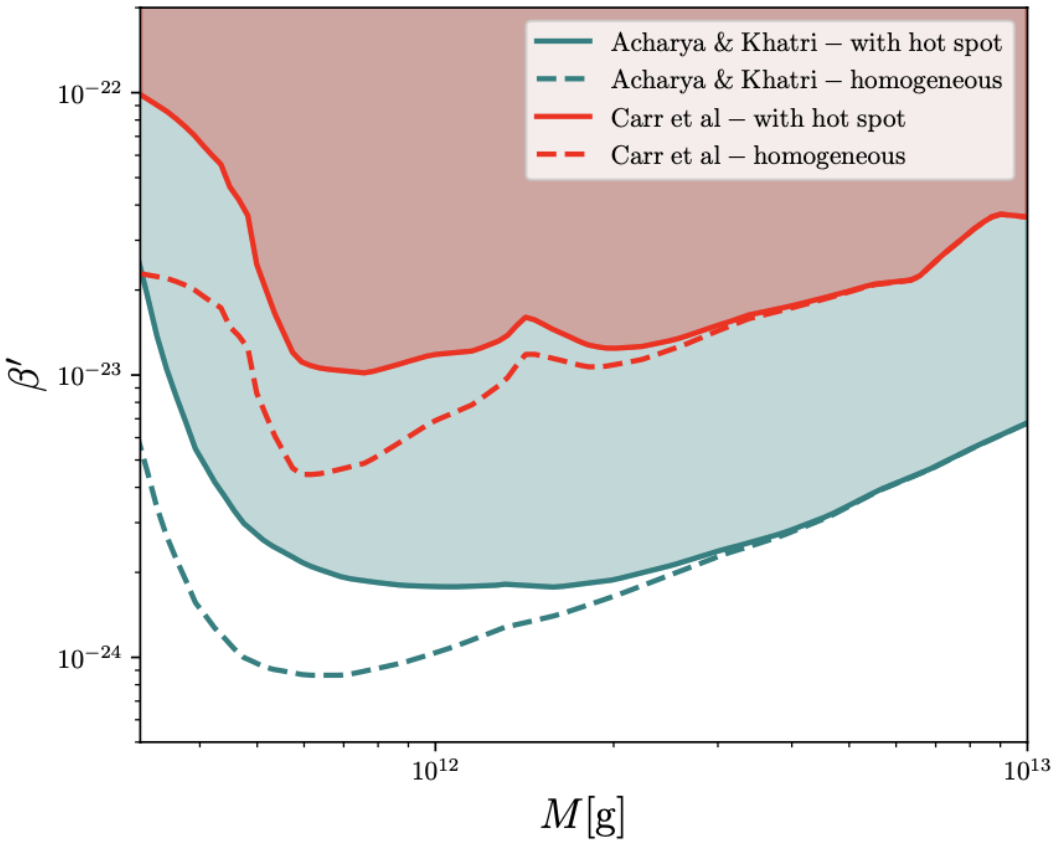


Fig. 2. Existing limits from Refs. [54] and [1] on the abundance of PBHs in the case where the Universe is assumed to be homogeneous (dashed lines) as compared to the case where the presence of a hot spot around PBHs is taken into account (plain lines).

Results

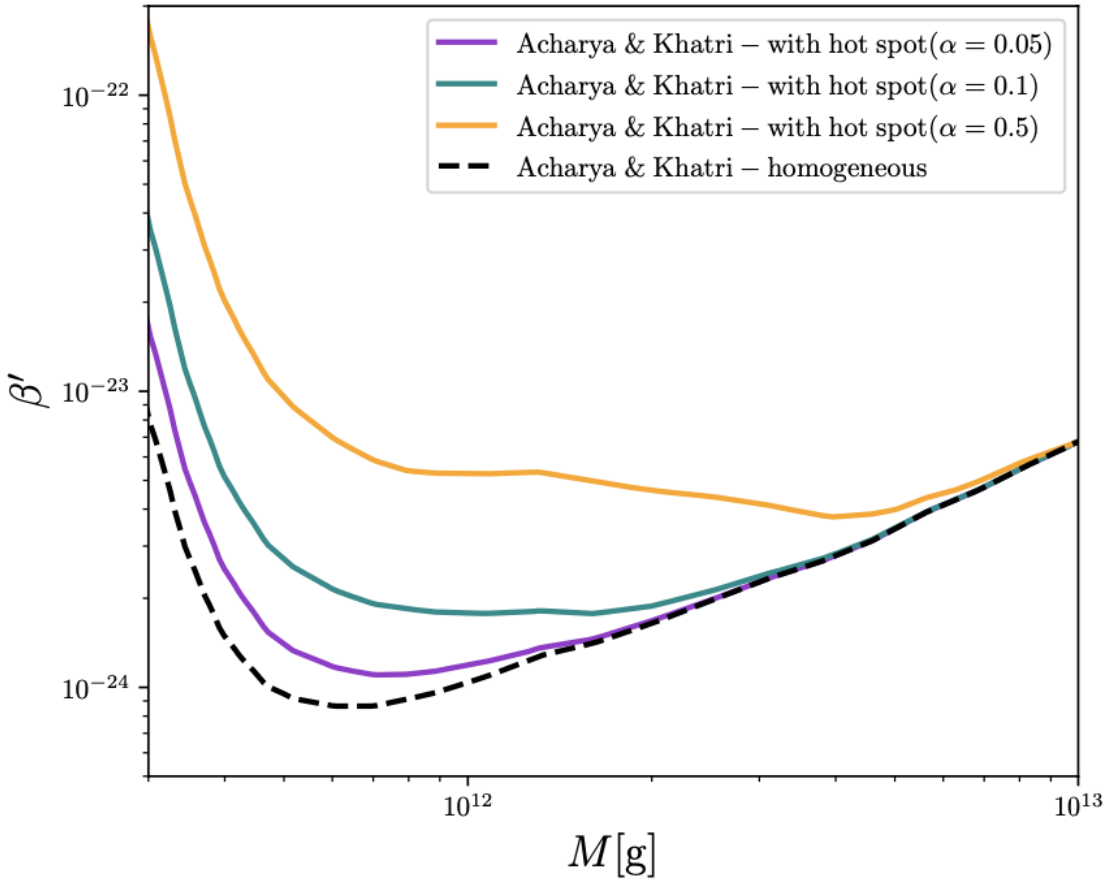


Fig. 3. Variation of the BBN limit on PBHs from photodissociation from Ref. [54] when fixing the coupling constant α to different benchmark values.

Summary

- **photodissociation** particularly releavant for 10^{11} g $\lesssim M \lesssim 10^{13}$ g;
- considered **shielding** and **black body radiation** effects;
- **universal spectrum** of low-energy photons reprocessed through scattering off the thermal plasma outside the hot spot compared against flux without hotspot;
- **drastic** effect for MeV-GeV photons emitted by PBH of $M = \mathcal{O}\left(10^{11} - 10^{12}\right) g$;
- **localisation** effects may be very relevant to PBH **BBN constraints**

Backup slides

- PBH basics
- Hotspot dynamics and caveats

PBH basics - backup

- **formation** from the collapse of super-horizon perturbations re-entering the horizon during radiation-dominated era.
- **monochromatic mass distribution**: M_i mass at formation, T_i Universe temperature at formation, H_i Hubble horizon at formation.

$$M_i = \frac{4\pi}{3}\gamma\frac{\rho_{\rm rad}\left(T_i\right)}{H_i^3} \sim 2\times 10^5\ {\rm g}\left(\frac{\gamma}{0.2}\right)\left(\frac{10^{13}{\rm GeV}}{T_i}\right)^2 \tag{12}$$

with $\gamma \sim 0.2$ grav. collapse factor for radiation dominated Universe, $\rho_{\rm rad}$ radiation energy density with temperature at formation.

PBH basics - backup

- **relative abundance** of PBHs at formation

$$\beta' \equiv \gamma^{1/2} \left(\frac{g_\star (T_i))}{106.75} \right)^{1/4} \frac{\rho^i_{\rm BH}}{\rho_{\rm rad} (T_i)} \tag{13}$$

where $\rho^i_{\rm PBH}$ = energy density of PBHs at that time, $g_\star (T_i)$ = number of relativistic degrees of freedom at formation.

- **Hawking radiation temperature**

$$T_H = \frac{1}{8\pi G M} \sim 10^4 {\rm GeV} \left(\frac{10^9 g}{M} \right) \tag{14}$$

- particle **emission rate** per E and t, particle species ℓ of mass m_ℓ, degrees of freedom g_ℓ, and spin s_ℓ, spin-dependent absorption probability $\vartheta(M, E)$

$$\frac{d^2 N_\ell}{dt dE} = \frac{g_\ell}{2\pi} \frac{\vartheta(M, E)}{e^{E/T_H} - (-1)^{2s_\ell}} \tag{15}$$

BPH basics - backup

- PBH **mass loss**

$$\frac{dM}{dt} = -\sum_{\ell} \int_{m_\ell}^{\infty} \frac{d^2 N_\ell}{dt dE} E dE \equiv -\varepsilon(M) \frac{M_p^4}{M^2} \tag{16}$$

  where $\varepsilon(M)$ = total effective evaporation function
- overall PBH **evaporation rate**: $\dot{M}/M \sim M^{-3}$
- initial evaporation rate at the PBH formation $\Gamma_{\rm ev} = \varepsilon\left(M_i\right) M_p^4/M^3$ $\rightarrow$ sets overall PBH evaporation time $t_{\rm ev} \sim \Gamma_{\rm ev}^{-1}$
- **evaporation starts** at $4H \approx \Gamma_{\rm ev} \rightarrow$ **Universe temperature**

$$T_{\rm ev} \equiv \left(\frac{90}{8\pi^3 g_\star\left(T_e v\right)}\right)^{1/4} \sqrt{\Gamma_{\rm ev} M_p} \tag{17}$$

  approximately constant over evaporation.

Hotspot dynamics and caveats - backup

$$M \gtrsim M_\star, \quad \text{where } M_\star \equiv 0.8 \text{ g} \left(\frac{\alpha}{0.1}\right)^{-\frac{11}{3}} \tag{18}$$

$$T(r) = T_c \times \begin{cases} 1, & r \leqslant r_c \\ \left(\frac{r_c}{r}\right)^3, & r_c < r \leqslant r_{\rm diff} \\ \left(\frac{r_c}{r_{\rm diff}}\right)^3 \left(\frac{r_{\rm diff}}{r}\right)^{7/11}, & r_{\rm diff} < r \end{cases} \tag{19}$$

where

$$r_c(M) \approx 8 \times 10^8 r_H \left(\frac{\alpha}{0.1}\right)^{-6} \left(\frac{g_\star(T_H)}{g_\star(T_c)}\right)^{-1}, \tag{20}$$

$$r_{\rm diff}(M) \approx 6 \times 10^{19} r_H \left(\frac{\alpha}{0.1}\right)^{-\frac{8}{5}} \left(\frac{106.75}{g_\star(T_H)}\right)^{\frac{4}{5}} \left(\frac{g_\star(T_{\rm diff})}{106.75}\right)^{\frac{1}{5}} \left(\frac{M}{10^9 \text{ g}}\right)^{\frac{6}{5}}, \tag{21}$$

$$T_c \approx 2 \times 10^{-4} T_H \left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} \left(\frac{g_\star(T_H)}{g_\star(T_c)}\right)^{\frac{2}{3}} \tag{22}$$

where $g_\star(T)$ = number of relativistic degrees of freedom at temperature T, T_H = Hawking temperature of BH, $T_{\rm diff} \equiv T_c\,(r_c/r_{\rm diff})$.

Hotspot dynamics and caveats - backup

At large r**:**

- $r_{\max} \equiv r_{\text{diff}}(M_i)$: **maximum distance** over which particles cannot diffuse within the lifetime of the BH.
- $T_{\text{ev}} \gtrsim T(r_{\max})$: **Universe temperature** during evaporation sets r_{max}
- **thermal equilibrium assumption**: $T(r) > \max(T_{\text{ev}}, m_e)$, $T(r) = T_{\text{ev}}$ otherwise